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ARCHAEAN PLATE TECTONICS REVISITED
1. HEAT FLOW, SPREADING RATE, AND THE AGE OF SUBDUCTING OCEANIC LITHOSPHERE AND THEIR EFFECTS ON THE ORIGIN AND EVOLUTION OF CONTINENTS

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Abstract. A simple model which relates the rate of seafloor creation and the age of the oceanic lithosphere at subduction to the rate of continental accretion can successfully explain the apparent differences between Archaean and Phanerozoic terrains in terms of plate tectonics. The model has been derived using the following parameters: (1) the spreading rate at mid-ocean ridges; (2) the age of the oceanic lithosphere at the time of subduction; (3) the area-age distribution of the seafloor; (4) the continental surface area as a fraction of the total surface area of the earth; and (5) the erosion rate of continents as a function of continental surface area and the total number of continental masses. Observations in Phanerozoic terranes suggest that there are profound differences in the nature and volume of subduction zone igneous activity depending upon the age of the oceanic lithosphere being subducted and the nature of the overriding plate (that is, either continental or oceanic). The subduction of young oceanic lithosphere (less than 50 m.y. old) which is thermally buoyant appears to result in a reduced volume of igneous activity. Most of the igneous activity caused by subduction of young oceanic lithosphere is either siliceous plutonism or bimodal tholeiitic-rhyolitic volcanism. When very young lithosphere is being subducted (<30 m.y. old), volcanism appears to cease. The subduction of old oceanic lithosphere (>50 m.y. old) appears to result in greater volumes of igneous activity, including the eruption of andesitic magmas. Thus andesites could only begin to be abundant in the rock record when older oceanic lithosphere began to be subducted. Our model predicts that as the earth aged and as heat flow from the interior of the earth diminished, the proportion of old oceanic lithosphere being subducted increased, fundamentally changing the nature of subduction zone igneous activity and the rate of continental accretion. If the subduction of old oceanic lithosphere results in an 8-10 times greater volume of subduction zone magmatism, our model predicts or explains all of the following observed features of earth history: (1) Archaean terranes appear to record two periods of rapid continental accretion, between 3.8 and 3.5 b.y. ago and between 3.1 and 2.6 b.y. ago; (2) there are very few differences and many marked similarities between rocks from Archaean terranes and equivalent rocks from Phanerozoic terranes; (3) the total continental area appears to have remained essentially constant for the past 2 b.y.

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(4) Archaean andesites are comparatively rare, and the relative abundances of mafic and siliceous rocks appear to change during the Archaean and the Proterozoic, with siliceous volcanics becoming proportionately more abundant in the geologic record with time; (5) plutonic tonalites and trondhjemites appear to have been relatively much more abundant during the Archaean. Plate tectonics is thus shown to have evolved over time due to a gradually decreasing rate of creation of oceanic lithosphere, meaning that Archaean tectonics and Phanerozoic tectonics are but two points on an evolutionary continuum.

INTRODUCTION

Previous Models of Archaean Tectonics

Over the past decade, a number of authors have published models of possible plate tectonic regimes for the Archaean and the early Proterozoic [Talbot, 1973; Drury, 1978; Bickle, 1978; Sleep and Windley, 1982; Arndt, 1983; Nisbet and Fowler, 1983]. In most of these models, the authors propose mechanisms by which the planetary heat production, postulated to have been greater in the Archaean than at present, could have been dissipated via plate tectonic processes. Bickle [1978] demonstrated that a higher rate of creation of oceanic lithosphere at Archaean spreading centers could have provided a very efficient mechanism for the removal of heat from the interior of the earth. Sleep and Windley [1982] solved the heat loss problem by assuming that Archaean oceanic crust was much thicker than at present. In order to explain the genesis of komatiites in terms of plate tectonics, both Arndt [1983] and Nisbet and Fowler [1983] suggested that the Archaean oceanic crust was much more ultramafic than at present as a result of a much hotter mantle. As pointed out by Bickle [1978], the high thermal gradients in the mantle which are required by the models of Arndt [1983] and Nisbet and Fowler [1983] are inconsistent with the metamorphic gradients deduced from Archaean high grade terranes. A critical problem for all of these models is the question of how Phanerozoic plate tectonics evolved from these proposed earlier regimes, and also, the authors do not extend their models to explain the origin and evolution of continents.

Talbot [1973] was the first to attempt such a unified plate tectonic model. However, at the time at which he wrote, the influences of plate tectonics upon continental accretion were poorly understood, so that he minimized the importance of subduction zone magmatism. Drury [1978] used a deductive approach to derive a unified evolutionary model. He intuitively derived the concept of buoyant subduction, but he mistakenly implied that there is no buoyant subduction at the present time. Also, his model is inconsistent with the experimental petrology of andesites and tonalites.

One of the difficulties in successfully modeling Archaean tectonics is the ambiguous complexity of the extant terranes. Although many authors have noted striking stratigraphic, mineralogic, and geochemical parallels between Phanerozoic and Archaean terrains (for example, Glikson [1972] and references cited by Windley [1976, 1977]), perceived differences and tectonic complexities have led some to reject plate tectonic analogues for the Archaean in favor of a model of global "vertical" tectonics [Glikson, 1972, 1981; Kroner, 1981a,b]. The concept that similar processes have been responsible for the similarities between Archaean and Phanerozoic terranes has often been vigorously resisted.

Problems in Archaean Tectonics

The central problem of Archaean field geology is the tectonic, geochronological, and geochemical relationships between greenstone belts and their enveloping terranes of granitic and tonalitic gneissic plutons. In some localities, the greenstone belts appear to have been deposited upon an older sialic basement, while in other areas they appear to have been intruded by younger sialic plutons. Reconciling these apparently contradictory field relationships is fundamental to an understanding of the origin and evolution of continental cratons and the early evolution of the crust. Deriving a unifying tectonic model from field and laboratory data is made difficult by the effects of high-grade metamorphism, insufficient outcrop exposure, and the relative inaccessibility of important field localities.

A related problem in attempting to

explain Archaean terranes in a plate tectonic framework has been the fact that, although given Archaean rock suites resemble in their compositions and associations similar Phanerozoic rocks created by plate tectonic processes, the relative abundances of rock types is different. In particular, certain rock types, such as tonalites, trondhjemites, and komatiites, are much more abundant in Archaean terranes [Windley, 1977]. Conversely, other rock types, such as andesites, are very rare in the Archaean [Condie, 1982]. These differences in relative abundance have been cited as evidence that Archaean tectonics were qualitatively different from Phanerozoic tectonics and that plate tectonics could not have occurred in the Archaean. In this paper, we explain how many objections to Archaean plate tectonics result from an incomplete understanding of Phanerozoic plate tectonic processes. We will show that differences between Archaean and Phanerozoic terrains can be explained with a simple model which relates the rate of ocean floor creation and the age of the oceanic lithosphere at subduction to the rate of continental accretion and that the differences between Archaean and early Proterozoic igneous suites and those of the Phanerozoic arise primarily from the more frequent subduction of very young (<50 m.y. old) oceanic lithosphere during the early history of the earth.

A factor not recognized until relatively recently is the complexity of Phanerozoic plate tectonic interactions and their resulting terranes. The phenomenal success of plate tectonic theory in explaining surface geological features of the earth's crust has sometimes masked the complexity of deep crustal structure and plate interaction. Horizontal tectonics in the Phanerozoic often are manifested at the surface as vertical movements of apparently great extent. For example, the deep seismic reflection profiles of the sub-surface structure of North America obtained by the COCORP project demonstrate that compressional forces at convergent plate margins can result in the development of large horizontal thrust sheets which are expressed at the surface as high angle thrust faults and extensive uplift [Brown et al., 1981]. Archaean and Phanerozoic tectonic styles may not differ so much in their extent of vertical motion, but only in that the more spectacular horizontal motions are more easily documented using paleontological and geophysical techniques in the better preserved Phanerozoic terranes.

The Problem of Archaean Heat Flow

It is generally accepted that the rate of terrestrial heat production has decreased approximately exponentially from the time of the earth's formation 4.5 b.y. ago through the Archaean and the early Proterozoic (3.8-2.0 b.y. ago) up to the present day [Lubimova, 1969; Lee, 1967]. Internal heat production during the Archaean is estimated to have been roughly three times the present value. The decrease in the rate of heat production over time has resulted in increasingly slower rates of overturn in the earth's mantle throughout its history [McKenzie and Weiss, 1975; Bickle, 1978]. At the present time, more than 65% of the earth's heat loss results from the creation of new oceanic crust at seafloor spreading centers [Sclater et al., 1981]. The exponential decrease of heat production and the consequent heat loss over the past history of the earth imply that the heat loss due to seafloor creation has also decreased approximately exponentially over time. Thus the rate of seafloor spreading and/or the total ridge length were much greater during the Archaean than during the Proterozoic.

Implications for the Origin of Continents

A gradual decrease in the rate of seafloor creation throughout the Earth's history seems difficult to reconcile with the evidence that the continents have remained at an essentially constant volume for the past 2 b.y. [McLennan and Taylor, 1982; Allegre et al., 1983]. Constant continental volume over a very long period of time appears to require that seafloor creation, and hence subduction rates, and the consequent continent-building igneous activity above subduction zones have also remained constant for the past 2 b.y. We propose here that constant continental volume is the result of a dynamic balance between erosion rates, subduction-related igneous activity, and seafloor creation rates. The dynamic balance arises from an apparent relationship between the age of the oceanic lithosphere at the time of subduction and the nature and extent of the resulting subduction zone magmatism [Sacks, 1983]. The subduction of oceanic lithosphere older than 50 m.y. ("old" lithosphere) results in less siliceous and more voluminous igneous activity, significantly affecting the nature and rate of continental accretion. Thus the rate of seafloor creation can slow, and the proportion of "old" lithosphere being subducted increase, while the rate of continental creation keeps pace with the erosion rate.

As seafloor spreading has slowed over time, the proportion of oceanic lithosphere older than 50 m.y. at the time of subduction has increased causing a progressive change in the nature of subduction zone magmatism. We will show that the genesis of progressively less siliceous and more voluminous magmas over time is the result of the interaction of three different variables: the age of the oceanic lithosphere at subduction, the nature of the plate overlying the subduction zone (that is, whether it is continental or oceanic), and the geothermal gradient (age) of the lithosphere beneath which the oceanic plate subducts. Archaean terranes were formed during a period of higher terrestrial heat loss as a result of the faster recycling of oceanic lithosphere via subduction zones.

In this paper, we show that the Archaean and the Phanerozoic have not differed fundamentally in nature but rather only in degree. The behavior of plates in modern-day subduction zones exhibits a great deal of variability and thus provides important clues for deducing the nature of plate tectonics in the Archaean. The model presented here demonstrates that the features observed in Archaean terranes resulted from the same sort of interactions which can be observed at the present time and not from exotic or speculative mechanisms beyond the limits of our observations.

OBSERVATIONS IN PHANEROZOIC TERRANES

Effect of the Thickness of Oceanic Crust on Buoyant Subduction

Total heat loss from the earth at spreading centers can be increased by solidifying thicker crust [Sleep and Windley, 1982], by increasing the rate of spreading, or by increasing overall ridge length. Because thicker oceanic crust results in bouyant subduction of older oceanic lithosphere (up to 70 m.y.; Sacks [1983)], it is important to decide if increased heat loss in the Archaean could have been the result of the production of thicker oceanic crust. Intensive geophysical and geochemical studies of the slow spreading Mid-Atlantic Ridge (MAR) (3 cm per year) and of the medium to fast spreading East Pacific Rise (EPR) (10-20 cm per year) have shown that there is no discernible difference between the thickness of normal oceanic crust created at the fast spreading sections of the EPR and that created at the MAR [Raitt, 1963; Sclater and Francheteau, 1970; Sclater et al., 1971]. Thus the rate of seafloor spreading by itself appears to have no effect upon the thickness of the oceanic crust [Reid and Jackson, 1981].

In conjunction with hot spot magmatism, the seafloor spreading rate does act as a major control on the ultimate thickness of the crust in a zone of hot spot activity. Areas of rapid upwelling in the mantle, surficially expressed as hot spots, can result in the creation of thicker oceanic crust. However, higher spreading rates modulate the effects of hot spot magmatism because more surface per unit time moves over a hot spot, thus very large accumulations of erupted material are less likely to occur on any particular section of a fast moving plate. For example, the surface area of thickened oceanic crust surrounding the Easter Island hot spot on the fast spreading EPR is much smaller than the region of thickened oceanic crust surrounding Iceland on the MAR. Even if rates of hot spot activity and seafloor spreading were proportionately greater during past earth history [Sleep and Windley, 1982], the average thickness of the oceanic crust was probably little different from that of the present [Bickle, 1978; Arndt, 1983].

Effect of Lithospheric Age on Buoyant Subduction

The age of the oceanic lithosphere at the time it is subducted has important effects on the nature of the subduction process and the resulting tectonics and magmatism. If the plate is young, it may be too buoyant to sink down into the mantle. In buoyant subduction [Sacks, 1983], the slab descends normally until it reaches a level of neutral density contrast with the surrounding asthenosphere and then it "floats" horizontally at this level. Sacks [1983] used seismic data on the subduction geometry of the Nazca Plate beneath Peru to model the occurrence of buoyant subduction. The incidence of bouyant subduction is dependent upon the thickness of the subducting crust relative to its age. Bouyant subduction occurs for relatively thin crust when it is younger than 40 m.y., for normal crust when it is younger than 50 m.y., and for relatively thick crust when it is younger than 70 m.y.

Buoyant Subduction Beneath Peru

The cause of buoyant subduction beneath central Peru was thought by Sacks [1983] to be the retardation of the transition from basalt to eclogite, which would otherwise increase the density of the slab causing it to sink further into the mantle, although this is not the only possible mechanism. After it is subducted beneath South America, the Nazca Plate appears to float directly beneath the overriding continental plate, upon the asthenosphere, for a distance of several hundred kilometers before sinking into the mantle [Sacks, 1983]. It appears that the relatively young Nazca Plate (approximately 40 m.y. old at the trench) is not dense enough to sink deeper than 100-150 km.

Sacks [1983] attributes this to the lower temperature of the mantle beneath continental lithosphere; that is, the temperature of the slab does not become high enough for the basalt-eclogite transition to occur anhydrously. However, in reaching this conclusion, he overlooked the effect of hydrothermal alteration on the water content of the subducting oceanic crust and the resulting conditions under which the basalt-eclogite transition would occur. Although he notes that water pressures of 10-30 kbar would lower the temperature of transition [Lambert and Wyllie, 1968; Essene et al., 1970], he asserts that the water content of ocean floor basalts is generally less than 1%. While it is true, as he cites, that basalt glasses have a very low volatile content in general, substantial quantities of water are added to the oceanic crust as a whole via hydrothermal circulation [Hart, 1973a,b]. Thus when oceanic crust subducts, after it has been hydrothermally altered, it may contain the 5-10% water which is required to lower the temperature of the basalt-eclogite transition.

Hydrothermal circulation causes the oceanic crust to decrease in density in two ways: (1) alteration of magmatic minerals to less dense hydrous minerals, and (2) fracturing of the basalt by penetration of seawater during convective cooling, exposing deeper levels of the crust to hydrothermal alteration. Furthermore, basalts erupted on anomalously shallow oceanic crust such as aseismic ridges in general have a greater proportion of vesicles than those erupted at normal mid-ocean spreading centers, which further reduces their density. The aseismic Nazca Ridge is buoyant because of the combined effects of increased thickness of extrusive rocks, increased depth of hydrothermal alteration, and increased vesicularity of extrusive rocks.

Buoyant subduction beneath Peru appears to be caused by two factors: (1) the relative youth of the Nazca Plate and (2) its anomalous thickness in the region of the aseismic Nazca Ridge where there is a larger proportion of less dense, hydrothermally altered crust relative to total lithospheric thickness.

Because oceanic lithosphere thickens with increasing age while the absolute thickness of the oceanic crustal section remains constant, the relative proportion of the low density component of the lithosphere (e.g., the crust) decreases with increasing lithospheric age. This means that young oceanic lithosphere is quantitatively less dense than old oceanic lithosphere and is therefore likely to subduct buoyantly.

Effect of Lithospheric Age on Petrogenesis in Subduction Zones

Two-stage melting processes have been shown to be necessary in order to satisfactorily explain the genesis of orogenic igneous rocks [Green and Ringwood, 1968; Barker and Arth, 1976; Arth et al., 1978]. In other words, rocks which have solidified from a magma derived from partial melting of the mantle, such as ocean floor basalts, are later subjected to partial melting

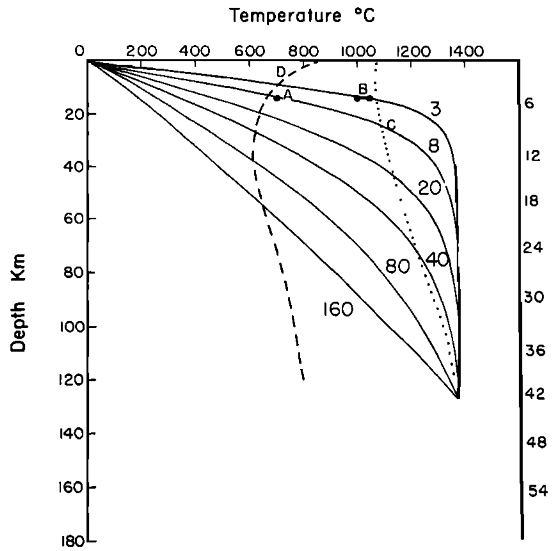

Fig. 1. Geotherms for oceanic lithosphere of six different ages, 3, 8, 20, 40, 60, 80, and, 160 m.y. (calculated from Parsons and Sclater [1977]) with melting data from experimental petrologic studies [Helz, 1976; Green, 1982] superimposed. The geotherm for 80-m.y.-old oceanic lithosphere closely resembles the geotherm for stable continental lithosphere [Oxburgh, 1980]. (a) Melting point for a tonalitic composition derived by melting a basaltic precursor [Helz, 1976]. (b) Melting range for andesitic compositions derived from basaltic precursors [Helz, 1976]. (c) Solidus curve for anhydrous andesitic melts [Green, 1982]. (d) Solidus curve for hydrous andesitic melts [Green, 1982]. Zones of crystal plus liquid are to the right of the solidus curves. Liquidus curves are not shown.

themselves, producing a more siliceous magma which could not be in equilibrium with mantle olivine. In the case of ocean floor basalts, the second melting stage is believed to occur in Benioff zones after the oceanic plate has been subducted.

Much emphasis has been placed on the importance of fluids migrating from the subducted slab [Hawkesworth, 1982; Weaver and Tarney, 1982]. Experimental work on the melting of basalt at $P(H_2O)$ equal to 5 kbar where $P(H_2O) = P_{total}$ [Helz, 1976] shows that magma of both andesitic (dioritic) and granitic compositions can be produced through partial melting of ocean floor tholeiites. In Helz's experiments, partial melting of 5-10% resulted in magmas with granitic compositions (SiO_2 content: 75-76 wt.%) Magmas of andesitic (dioritic) compositions (SiO_2 content: 56-65 wt.%) required 6-10 times more partial melting of tholeiites or alkali basalts than granitic melts. The silica content of the melts produced decreased almost linearly with increasing temperature. Helz [1976] states that the nearest natural analogues to small partial melts of tholeiites at T circa 700°C and a $P(H_2O)$ equal to 5 kbar are rocks of the trondhjemitic suite (Figure 1a). Andesitic (dioritic) melts form at T about 1000-1045°C at the same pressure (Figure 1b).

Figure 1 shows calculated geotherms for oceanic plates of different ages [Parsons and Sclater, 1977]. If one assumes that the upper surface of each curve represents the thermal regime encountered by a subducting oceanic plate, these calculated geotherms can be used in conjunction with anhydrous and hydrous solidus curves for andesitic compositions (Figure 1c and d, from Green [1982]) and the experimental results obtained by Helz [1976] to model the generation of subduction zone magmas (Figure 1).

It seems reasonable to conclude from the data of Helz and the calculated oceanic geotherms that buoyant subduction would lead to partial melting at a shallower depth in the mantle, where initially lower temperatures (about 700°C) and pressures (5-10 kbar) would cause small amounts of partial melting of the subducting slab, producing siliceous melts. If, as indicated by Helz's experiments, these initial melts have tonalitic or trondhjemitic compositions, this provides an important clue to the origin of the well-known Archaean tonalitic and trondhjemitic plutonic rocks. It might be inferred that as the slab descends and as more partial melting occurs, the melts will progressively decrease in silica content, becoming more dioritic in composition. Where the overriding plate is continental, this could also cause extensive melting of the overlying plate. In fact, continental crustal contamination of lavas has been observed in the central volcanic zone of South America [Harmon et al., 1983; Thorpe, 1983; James, 1983].

A further important inference is derived from examination of calculated oceanic geotherms (Figure 1). The geotherm for 20 m.y. oceanic lithosphere has a significantly shallower slope than that for 80 m.y. oceanic lithosphere. If 20 m.y. lithosphere is subducted, it retains a significant amount of heat compared to lithosphere which is older, and will thus more rapidly attain thermal equilibrium with the mantle into which it subducts. Subduction rate would also affect thermal equilibration of a subducting plate. Older lithosphere has a higher convergence rate [Carlson et al., 1983] and will therefore descend farther before attaining thermal equilibrium. Younger, more buoyant lithosphere descends more slowly and thus has more time at a given depth to equilibrate with the surrounding mantle. At the same time, the thermal decomposition of hydrous and carbonate phases will liberate CO_2 and H_2O, causing an increase in $P(CO_2)$ and $P(H_2O)$. It appears likely that the very siliceous magmas will be derived from partial melting of the slab before it sinks deeper into the mantle. Decomposition of amphibolite and serpentine minerals at greater depths will release volatiles into the overlying asthenosphere.

Consequently, the subduction of young lithosphere beneath oceanic lithosphere of similar age and composition, a reasonable approximation of Archaean conditions, would likely produce two types of melts from two different source regions: siliceous magmas derived from shallow melting of the subducting slab under high $P(H_2O)$, and basaltic magmas derived from deep melting of the overlying asthenosphere under low $P(H_2O)$.

This also provides an elegant mechanism for the generation of komatiites. Allegre [1982] has pointed out that if wet peridotite is assumed to be the source region for komatiites, the solidus temperature of these highly magnesian lavas is depressed. In Allegre's model, the subducting crust is itself ultramafic, but in the model presented here, the ultramafic source for komatiite melts is in the mantle wedge, while the subducting plate is the source of the fluids which induce melting. In our model, which shares many similarities with the model of Weaver and Tarney [1979], komatiites result from the deep melting of the mantle wedge due to the subduction of young oceanic lithosphere. Later in this paper, we show that this is a reasonable description of subduction during the Archaean and the Early Proterozoic.

Tectonic Controls on Volcanism

Elder [1981] states that the thickness of the overlying crust controls the onset of volcanic activity. While the thickness of the overlying crust is important, crustal thickness is a second order effect compared to depth of magmatic origin. For example, the thickness of the continental crust in La Paz, Bolivia, is 65 km, yet active volcanism is present.

The depth of magma generation affects the elevation to which the melt may rise, both directly, by affecting the length of the magma column in the mantle, and indirectly, by affecting the silica content and therefore the viscosity of the magma. For a given initial water content and temperature, a partial melt of the slab will be more siliceous and more viscous than a partial melt of the asthenosphere. As pressure (depth) increases, the percentage of partial melt increases, causing a decrease in silica content and melt viscosity.

A magma column can be modeled as a two stage manometer containing melt which contrasts in density with the surrounding mantle and crust. The average density contrast between melt and mantle is 3 times the average density contrast between melt and crust [Elder, 1981, p. 90 and Figure 2]. The length of the column in the mantle provides most of the driving force for the rise of partial melt through the crust [Elder, 1981, p. 84]. Other factors being equal, magmas which originate at shallow mantle depths cannot rise as high in the crust as magmas derived from more deep-seated sources. Because the density contrast throughout the entire column controls the rise of material, this model explains why basic magmas can rise through surface sediments which have a lower density than the melt. This model also explains the inference of Barazangi and Isacks [1976, 1979] and Grange et al. [1984], that volcanism requires a wedge of asthenosphere between the overriding and subducting plates.

Shallower depths of magma origin

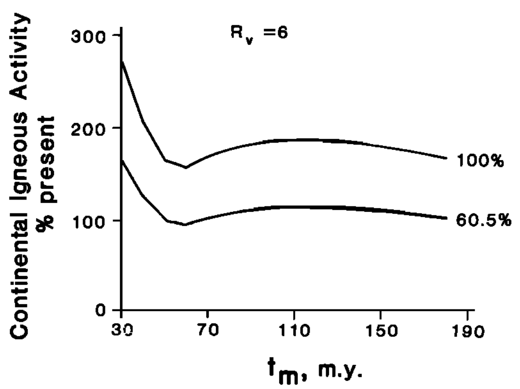

Fig. 2. Continental igneous activity as a percentage of present day activity plotted versus the maximum age of the oceanic lithosphere at subduction, t_m; 100% of present day activity is assumed to correspond to a R_v equal to 6:1 where R_v is defined as the volume of igneous activity due to the subduction of old (>50 m.y.) lithosphere relative to that due to the subduction of young lithosphere for an earth on which the oceans cover 60.5% of the total surface area (the present value).

caused by buoyant subduction will therefore more likely result in the emplacement of silicic plutons rather than in the surface eruption of siliceous magmas. However, the deep generation of picritic magmas beneath the back arc region of a young subducting slab would result in surface eruption of picrites where the overriding slab is oceanic and would induce melting of preexisting sialic material where the overriding slab is continental, resulting in the generation of a wide range of magmatic types.

In the most well-studied examples of modern subduction zones where the downgoing slab is young and buoyant (<50 m.y. old), the overriding slab is generally continental. Regions which have been studied include central Peru [Sacks, 1983], the northwest United States [Langston, 1979, 1981], Alaska and the eastern Aleutians [DeLong and Fox, 1977; Jacob et al., 1977], Southwest Honshu-Kyushu, Japan [Sacks, 1983; Nur and Ben-Avraham, 1981], and the Sulawesi Trench between Borneo and the Phillipines [Hamilton, 1979; Cardwell et al., 1980]. In these areas, there seems to be markedly less seismic activity and volcanism than in areas of "normal" subduction. Some subduction zones involving young (<50 m.y.) seafloor appear to have no volcanism at present [Sacks, 1983], while others have less voluminous but more silicic volcanism. Along the northwest coast of the United States, the young Juan de Fuca plate is being subducted beneath the North American plate. Overall seismic activity due to plate subduction is low when compared to trenches where older lithosphere is being subducted. However, petrological comparisons are complicated due to possible contamination by overlying continental and hot spot material [McBirney, 1969; McBirney and White, 1982; Duncan, 1982]. In the Aleutian Island arc, where old oceanic lithosphere of the Pacific plate is being subducted, there are much more frequent eruptions and more andesitic magmas than in the Cascades [Kay, 1977]. In the eastern part of Alaska, where younger crust is being subducted, there is also less volcanism and less seismic activity [Jacob et al., 1977; Stevens et al., 1983]. In all cases, differences in volcanic character appear to be related to the behavior of the subducting slab which is dependent upon its thickness, age, and convergence rate.

Effect of Ridge Subduction

DeLong and Fox [1977] modeled the topographic and thermal consequences of the subduction of a spreading ridge in relation to the geology of the Aleutian arc where the Kula Ridge was subducted 30-35 m.y. ago. Besides the cessation of magmatism in the Aleutian arc between 45 and 15 m.y. ago, the arc lithologies record a pervasive greenschist metamorphic event at the same time as the ridge is believed to have passed beneath it. The crest of the arc was also uplifted above sea level, leading to the deposition of shallow water and subaerial sediments. Once the subduction of the Kula Ridge was complete, the crest of the arc again subsided and volcanism resumed [DeLong and Fox, 1977]. If, as we postulate, the likelihood of ridge subduction was greater in the Archaean and the Proterozoic due to more rapid spreading rates, this sequence of events should have been recorded many times in Archaean and Proterozoic rocks. Cycles of greenschist facies metamorphism in concert with calc-alkaline igneous activity are in fact extensively preserved in the Precambrian strata of Canada [Goodwin and Ridler, 1969; Gelinas et al., 1977a,b; MacGeehan and MacLean, 1980].

In the southwest Pacific, tectonic conditions exist which may be analogous to conditions in the Archaean and early Proterozoic. For example, young oceanic lithosphere is being subducted beneath oceanic lithosphere along an approximately 400 km section of the Sulawesi Trench [Hamilton, 1979]. The subducting lithosphere from the Celebes basin has a probable age of less than 42 m.y. [Weissel, 1980] and the east-west striking portion of the North Sulawesi arc has weak seismicity and no Quaternary volcanism [Cardwell et al., 1980]. We infer that both the absence of recent volcanism and the weak seismicity are due to the buoyant subduction of young oceanic lithosphere.

Effect of the Seafloor Creation Rate on Subduction Zone Magmatism

The rate at which ocean floor is created and the average rate of subduction are mutually dependent. If the total surface area of the earth and of the continents is constant, an increase in the rate of seafloor creation must result in a concurrent increase in the rate of subduction. The maximum age of the oceanic lithosphere at any time in earth history is a function of only two variables: the rate of plate creation and the total oceanic surface area. If either of these were to change, the proportion of seafloor of a given age at subduction would also change. In the present oceans, the distribution of area with age is indistinguishable from that expected from a steady state distribution [Parsons, 1982], so that the response time to changes in either of the variables must be very long.

Marine transgressions in the Cretaceous have been very well documented, and Hays and Pitman [1973] have demonstrated that increases in global spreading rates could have caused them. Seafloor older than 60 m.y. still remains unsubducted at the present time, but there is no marked increase in area relative to age for Cretaceous seafloor [Parsons, 1982]. This implies that the area-age distribution is quite stable relative to changes in the spreading rate over a period of a few million years. Thus while the seafloor spreading rate may have varied in the Phanerozoic, large increases or decreases for longer periods of time are required in order to substantially alter the area-age distribution. At the present time, the maximum age of subducting lithosphere is approximately 180 m.y. [Parsons, 1982]. If seafloor spreading rates were to increase for a period longer than a few million years, the area-age distribution of the seafloor would change and the maximum age of oceanic lithosphere at subduction would decrease.

As previously discussed, the age of the subducted oceanic lithosphere may significantly affect the amount and type of igneous activity at convergent plate margins. Consequently, the area-age distribution of the oceanic lithosphere will directly influence the rate of continental accretion. Actual differences in quantity and composition of igneous activity between Cenozoic plate boundaries where young lithosphere is being subducted and those where the subducting slab is old have not been studied in detail. However, based upon the amount of partial melting of the slab needed to produce a rhyolitic as compared an andesitic melt [Helz, 1976], one can define a volume ratio of emplaced igneous material for buoyant (young lithosphere) subduction relative to nonbuoyant (old lithosphere) subduction which ranges between 1:6 and 1:10. Thus in areas where older lithosphere is subducted and subduction is nonbuoyant, 6-10 times the volume of igneous material will be generated relative to those areas where buoyant subduction of young lithosphere is occurring. This may be a conservative estimate because in some areas where young lithosphere is being subducted there is no volcanism [Sacks, 1983].

CHARACTERISTICS OF ARCHAEAN TERRANES

Despite the lack of general agreement on possible models for Archaean tectonics, there are a few specific points which are widely accepted:

1. Surface heat flow in the Archaean was greater than that of the present day, with estimates ranging to more than 3 times present values [Lubimova, 1969; Bickle, 1978; Burke and Kidd, 1978].
2. There appears to be a marked

difference in "tectonic style" between the Archaean and the Proterozoic, although the exact nature of the difference and its causes are disputed. Furthermore, the Archaean-Proterozoic boundary appears to vary in age from terrain to terrain [Windley, 1977; Clemmey and Badham, 1982; McLennan and Taylor, 1982].

3. There appears to have been a period of rapid continental accretion in the late Archaean and the early to middle Proterozoic with vast volumes of material being added in some areas [Moorbath, 1975a,b; Windley, 1977; McCulloch and Wasserburg, 1978; McLennan and Taylor, 1982].

4. Early sialic magmatism was dominantly plutonic and tonalitic in character. Extrusive members of the calc-alkaline suite became abundant only much later in the geologic record [Glikson, 1972; Barker and Arth, 1976; Arth and Barker, 1976; Weaver and Tarney, 1982]; Archaean andesites are rare [Condie, 1982].

5. There are broad lithological, stratigraphic, and geochemical similarities between rocks from Archaean terrains and equivalent rocks from Phanerozoic terrains [Boutcher et al., 1966; Anhaeusser, 1975; Windley, 1977; Eriksson, 1977, 1979; Barley et al., 1979; de Wit et al., 1980, 1982; Clemmey and Badham, 1982].

Attributes Of An Archaean Plate Tectonic Regime

Given these generalizations and taking into account pertinent aspects of Phanerozoic tectonics, we can postulate the attributes of a plausible Archaean plate tectonic regime:

1. Assuming that the higher heat flow in the Archaean reflects a more rapid rate of convective overturn in the mantle during that time [Schubert et al., 1979, 1980; McKenzie and Richter, 1981], rates of seafloor spreading in the Archaean would have been greater.

2. Higher Archaean heat flow might also have expressed itself surficially in a greater overall ridge length [Burke and Kidd, 1978; Weaver and Tarney, 1979] and a correspondingly greater overall trench length.

3. It follows from assumptions 1 and 2 that surface plates in the Archaean would have been smaller and that there would have been a greater frequency of triple junctions [Drury, 1978].

4. It also follows from 1 and 2 that the average age of the Archaean oceanic lithosphere at the time of subduction would have been much younger than at present.

5. The probability of a spreading ridge being subducted was correspondingly greater.

6. At the beginning of the Archaean, approximately 3.9 b.y. ago, there were essentially no discreet continental masses [McLennan and Taylor, 1982].

7. Hence when subduction occurred, young oceanic lithosphere formed both the overriding plate and the subducting plate, with differences in density determining which plate would descend into the mantle.

MODEL RELATING CONTINENTAL ACCRETION RATE TO THE MAXIMUM AGE OF SUBDUCTED OCEANIC LITHOSPHERE

Based upon observations in Phanerozoic terrains and inferences on the nature of Archaean tectonics, we have constructed a model for the evolution of the crust based upon the following parameters: (1) spreading rate and, hence, subduction rate; (2) the age of the oceanic lithosphere at the time of subduction; (3) the area-age distribution of seafloor; (4) the continental surface area as a fraction of the earth's surface; and (5) the erosion rate of continents as a function of total continental surface area and number of continental masses.

Our model for the accretion of continents over the history of the earth has five basic assumptions:

1. The ratio, R_y of igneous activity per unit area of old lithosphere subducted relative to young lithosphere subducted is between 6:1 and 10:1.

2. The maximum age of subducted oceanic lithosphere , t_m, has increased linearly throughout earth history.

3. Continental accretion began approximately 3.8-3.9 b.y. ago.

4. Continental erosion rates are roughly proportional to the square root of total continental surface area and the total number of continental masses.

5. The present rate of continental erosion is approximately steady state; that is, the material eroded balances the amount of new continental material added

via igneous activity [Holland, 1978].

Observations of modern seafloor spreading centers and subduction zones allow us to deduce the manner in which these parameters interact to produce the observed terrains. The rate of continental accretion as a function of the maximum age of the oceanic lithosphere, t_m, for a constant rate of change of t_m has been modeled using extensions and modifications of the work of Parsons [1982]. Accretion of the present-day continental mass was a slow process requiring about 2 b.y. [McLennan and Taylor, 1982; Allegre et al., 1983]. Because continental surface area increased slowly (and thus oceanic surface area decreased slowly), at any time in earth history, the total rate of seafloor creation, C_o, and the subduction rate can be assumed to be approximately equal.

The area of ocean floor of a given age is controlled by the total area of the ocean basins and the seafloor creation rate. From the area-age distribution of the present-day seafloor, it appears as if initiation of subduction is a random process which does not depend on the age of the seafloor [Parsons, 1982]. However, there is an upper limit on the age of the ocean floor at the present time. Let $A_o(t,T)$ be the area of ocean floor with age less than or equal to t at time T in earth history. Therefore there is a maximum age, $t_m(T)$, of seafloor that exists at any time, T. All ocean floor has been or is being subducted at trenches by the time it reaches a certain maximum age, t_m. This maximum age of the oceanic plate at the time of subduction is dependent only upon the total area of the ocean floor, $A_o(t_m,T)$, and the rate of creation of new ocean floor, C_o:

$$t_m(T) = 2A_o(t_m,T)/C_o \qquad (1)$$

Our model assumes that the maximum age of seafloor at subduction, $t_m(T)$, has increased over time and was therefore much younger during earlier periods of earth history. Thus in the Archaean and the Proterozoic, relatively young oceanic crust was being subducted at a much greater rate than at present.

The primary control on $t_m(T)$ is $C_o(T)$, the rate of seafloor creation. C_o can be increased and t_m can be decreased by two processes: increasing global seafloor spreading rates or by increasing total global ridge length. Our model is not sensitive to the method by which the maximum age of the plate at subduction is changed, although it is reasonable to believe that the two processes both were active simultaneously.

During the earliest history of the earth (4.5-3.9 b.y. ago), the earth's crust was being constantly remelted by the heat generated by meteorite impacts [Frey, 1980; McLennan and Taylor, 1982]. During this period, the maximum age of any piece of solidified crust would have been very young. Once mantle convection had become established and the frequency of meteorite impacts diminished substantially (roughly 3.9 b.y. ago), seafloor spreading and the rapid recycling of oceanic lithosphere would have commenced. About 3.8 to 3.9 b.y. ago, this rapid overturn of the oceanic crust began to result in the formation of continents [Windley, 1977]. These early continents had a much higher proportion of plutonism to volcanism and negligible amounts of andesite [Windley, 1977]. The first greenstone belts which contain moderate amounts of andesite formed about 3.4 b.y. ago. Furthermore, the abundance of andesite in greenstone belts increases as a function of stratigraphic height [Condie, 1982]. If this change in the character of igneous activity can be attributed to changes in the maximum age of the oceanic lithosphere at subduction, then it implies that oceanic lithosphere older than 50 m.y. began to be subducted roughly 3.4 b.y. ago.

For a maximum age at subduction, t_m, equal to 38.5 at 3.8 b.y. ago and equal to 180 m.y at the present time, t_m can be assumed to vary linearly with the age of the earth. A linear increase in t_m produces a roughly exponential decay in the rate of heat loss due to seafloor creation with the increasing age of the earth, and it is also consistent with the initiation of andesite magmatism about 3.4 b. y. ago. Continental surface area, $A_c(T)$, is equal to the total surface area, A_e, minus the surface area of the ocean basins, A_o:

$$A_c(T) = A_e - A_o(t_m,T) \qquad (2)$$

For a linear and slow rate of change of t_m, equation (1) can be modified to solve for the rate of plate creation, C_o, for any given continental surface area:

$$C_o = 2[A_e - A_c]/t_m \tag{3}$$

As previously discussed, the subduction of young, buoyant oceanic lithosphere apparently results in 6-10 times less igneous activity than the subduction of old (>50 m.y.) ocean floor. Furthermore, the area-age distribution of all ocean floor in the present day is the same as the area-age distribution of the ocean floor in subduction zones. The area-age distribution and the total amount of oceanic lithosphere being subducted are therefore the two factors controlling the primary source of new continental material, that is, subduction-related igneous activity.

The area of ocean floor that is less than or equal to a given age, t, at the present time, T_o, in earth history is [Parsons, 1982]:

$$A_o(t, T=T_o) = C_o\, t \left[1 - \frac{t}{2t_m} \right] \tag{4}$$

The fraction of ocean floor, F(t,T), being subducted which is younger than a given age, t, is:

$$F = \frac{A_o(t,T)}{A_o(t_m,T)} = \left[\frac{2t}{t_m} \right] \left[1 - \frac{t}{2t_m} \right] \tag{5}$$

The rate at which continent-building igneous activity, C_c, occurs is dependent upon (1) the seafloor creation rate, C_o, and hence, the subduction rate; (2) the ratio, R_v of volumes of igneous activity resulting from the subduction of old (>50 m.y.) oceanic lithosphere versus young (<50 m.y.); R_v is greater than or equal to 6:1; (3) the ratio, G, of the amount of the oceanic lithosphere which has been subducted and subjected to secondary melting to the amount of the resultant continental crust; G is a coefficient which has been iteratively adjusted in our model to cause the results to converge upon the present continental surface area; and (4) the fraction, P_m, of partial melt generated at zones of subduction of young (<50 m.y.) lithosphere. Thus

$$C_c = \left[\frac{C_o P_m}{G} \right] [F + (1-F)V_r] \tag{6}$$

Figures 2 and 3 show continental igneous activity as a percentage of present day activity for differing total oceanic surface areas, A_o, and differing values for R_v and t_m. For values of t_m between 30 and 40 m.y., the continental igneous activity is higher because the amount of oceanic lithosphere being subducted is greater. The total amount of igneous activity decreases until t_m reaches 50 m.y. At this time, the genesis of andesites begins and more extensive volcanic activity occurs wherever old (>50 m.y.) oceanic lithosphere is being subducted. For R_v between 8:1 and 10:1, continent-building igneous activity reaches a maximum between t_m of 90-120 m.y. For values of t_m greater than 120 m.y., decreasing rates of subduction nearly balance the increased volcanism which results from the subduction of an increasing quantity of old oceanic lithosphere, leading to a

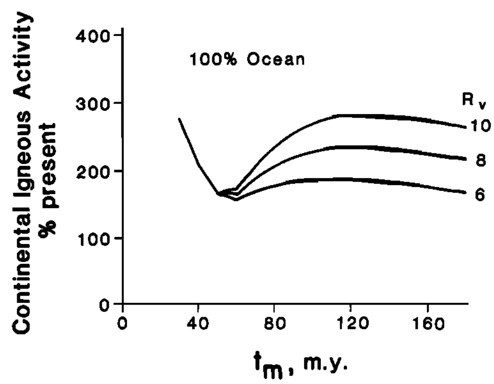

Fig. 3. Continental igneous activity as a percentage of present day activity plotted versus maximum age of oceanic lithosphere at subduction. Curves are obtained for R_v equal to 6:1, 8:1, and 10:1, where R_v is defined as the ratio of the volume of igneous activity due to the subduction of old lithosphere to that due to the subduction of young lithosphere. All curves are for an entirely marine crust. 100% of present day igneous activity is assumed to correspond to a R_v of 6:1 with a continental surface area equal to that of the present.

dynamic balance between total continental surface area and total oceanic surface area.

In Figure 4, the ratio of the magmatic activity resultimg from the subduction of old oceanic lithosphere to the magmatic activity resulting from the subduction of young oceanic lithosphere is plotted versus the maximum age of oceanic lithosphere at subduction, t_m. Three curves were generated for R_v equal to 6, 8, and 10. An implication of this figure is that the more rapidly continental crust is accreted, the more rapidly the oceanic crustal recycling mechanism is slowed. Figures 2, 3, and 4 imply that there is a sensitive feedback mechanism connecting the overall quantity and rate of accretion of continental crust with the processes which result in the creation of new ocean floor.

The changes in the volume and nature of igneous activity which accompany the transition from the subduction of young oceanic lithosphere (<50 m.y.) to the subduction of old oceanic lithosphere (>50 m.y.) are also accompanied by changes in the relative abundance of rock types. Thus the proportion of "young" subduction zone igneous suites to "old" subduction zone igneous suites will decrease as t_m increases (Figure 4) and as the age of the earth increases. Igneous rocks which should be more abundant in areas where young lithosphere is being subducted include bimodal suites of tonalitic, dacitic, and basaltic compositions, komatiites, and trondhjemites. Plutonic rocks should be more abundant in areas where young lithosphere is being subducted because of the shorter length of the "mantle manometer". Conversely, in areas where old lithosphere is being subducted, extrusive rocks of the andesite-rhyolite suite should be more abundant. How the nature of continent-building igneous suites generated in subduction zones varies depending upon the age of the oceanic plate being subducted is a new but potentially productive area of research. There are also some indications that the age of the overriding plate and the nature of the overriding plate (either continental or oceanic) can affect the nature of subduction zone igneous suites. This is discussed in more detail in a companion paper [S.F. Hoffman and D.A. Abbott, manuscript in preparation, 1984].

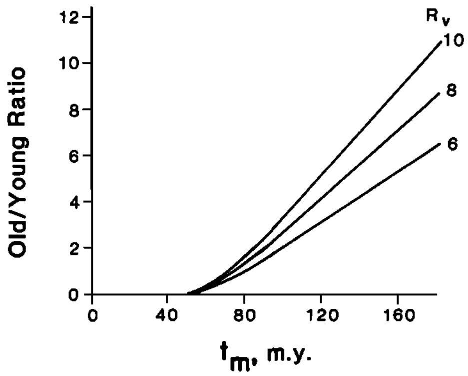

Fig. 4. The ratio of igneous suites resulting from the subduction of old (>50 m.y.) lithosphere relative to those resulting from the subduction of young lithosphere, plotted versus the maximum age of the oceanic lithosphere at subduction, t_m.

Erosion Rates and Continental Accretion

In order to integrate the concept of igneous activity as a function of the area-age distribution of subducted oceanic crust into a more complete model of continental accretion, continental erosion rates must be considered. Only erosion which completely removes material from the continental surface area is considered.

The total distance an eroded particle must travel to reach the ocean is proportional to the square root of the continental surface area (of a circular continent). If the total number of continental masses had remained constant throughout geologic time, erosion rates would be proportional to the square root of the total continental surface area. In fact, the probability that continental masses will collide to produce larger continental masses increases with the total continental surface area (and also with seafloor creation rates). Therefore continental erosion rates during past earth history are estimated to be proportional to the square root of the total continental surface area and to the total number of continental masses. The present-day erosion rate, E_r, approximately balances the addition of

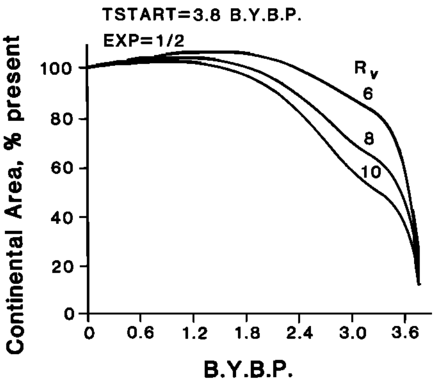

Fig. 5. Continental surface area expressed as a percentage of present-day continental surface area versus time in billions of years before present. The initiation of continental accretion, TSTART is assumed to be 3.8 b.y. ago, and the erosion rate is assumed to be proportional to the square root of the total continental surface area (EXP=1/2). Modeling was done for R_v equal to 6:1, 8:1, and 10:1.

new continental material [Holland, 1978]. Past continental erosion rates, C_{ss}, are given by

$$C_{ss} = E_r \left[\frac{A_c(T)\ N(T)}{A_c(T_o)\ N(T_o)} \right] \qquad (7)$$

where $A_c(T)$ is the area of the continents at a time, T, in earth history, T_o is the current age of the Earth, and N(T) is the number of continental masses at any time, T. For the purposes of this initial work, the number of past continental masses was assumed to equal the present number of continental masses. To simulate the effect of a larger number of continental masses in early earth history, we used an exponent of 1/3 rather than 1/2 for half of our model calculations of C_{ss}.

We performed a numerical integration of the equation:

$$dA_c(T)/dT = C_c(T) - C_{ss}(T) \qquad (8)$$

where $A_c(T)$ is the area of the continents, C_c is the rate of addition of new material to the continents, and C_{ss} is the rate of removal of material from the continents. The numerical integration was performed at 10 m.y. intervals from 3800 m.y. ago until the present, while G was iteratively adjusted until

$$A_c(T=T_o) = A_c(\text{observed today}) \qquad (9)$$

That is, the integration must converge upon the present continental surface area. Total continental surface area is not required to increase with time, so erosion may decrease continental surface area if addition of new continental material is too slow.

The results of the numerical integration predict continental surface area as a percentage of the present continental surface area for the past 3.8 b.y. (Figures 5 and 6). The model was run for values of R_v between 6:1 and 10:1 and for erosion rate exponents of 1/2 and 1/3. The shapes of the curves of continental surface area plotted versus the age of the earth are basically the same for the six different models. Decreasing the erosion exponent from 1/2 to 1/3 slows the initial rate of continental accretion but has little effect upon the predicted continental surface area for the past 2 b.y. Increasing R_v produces a plateau in continental accretion rate between 3.6 and 3.3 b.y. ago and decreases the difference between the maximum continental surface area and the present-day continental surface area.

GEOPHYSICAL TEST OF THE MODEL

In order to test the reasonableness of our model, we calculated the terrestrial heat loss (heat flow) which would result from an increased rate of seafloor production during early earth history. The total heat flow, Q, released through seafloor creation is given by the equation [Parsons, 1982]:

$$Q(t_m) = \frac{2K_1 T_m C_o}{[\pi K_2]^{1/2}} \left[\frac{2}{3} [t_m]^{1/2} \right] \qquad (10)$$

where K_1 is the thermal conductivity, K_2 is the thermal diffusivity, T_m is the melting temperature of the rock, C_o is the rate of seafloor creation, and t_m is the maximum age of subducted lithosphere.

The ratio of heat flow due to seafloor creation between the present, T_o, and the past, T, is

$$\frac{Q(T)}{Q(T_o)} = \frac{B\, C_o(T)}{C_o(T_o)} \left[\frac{t_m(T)}{t_m(T_o)} \right]^{1/2} \qquad (11)$$

where B is a constant (Figure 7).

In Figure 7, heat flow is plotted versus time in billions of years before present. For a linear rate of change of t_m and N(T)=0 at 3.8 b.y., the terrestrial heat loss due to ocean floor creation 3.8 b.y. ago would have been 3.4 times the present heat loss due to the same process. The rate of terrestrial heat production due to the decay of radioactive isotopes 3.8 b.y. ago is estimated to have been approximately 3.4 times the present value [Lubimova, 1969, after Lee, 1967]. The model is consistent with the assumption that there has been a nearly constant ratio of heat loss due to seafloor

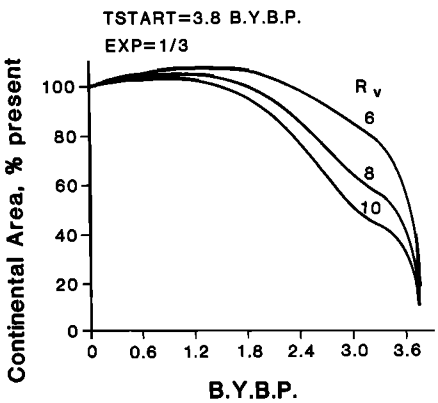

Fig. 6. Continental surface area expressed as a percentage of present day continental surface area versus time in billions of years before present. The initiation of continental accretion, TSTART is assumed to be 3.8 b.y. ago, and the erosion rate is here assumed to be proportional to the cube root of total continental surface area (EXP=1/3). Modeling was done for R_v equal to 6:1, 8:1, and 10:1.

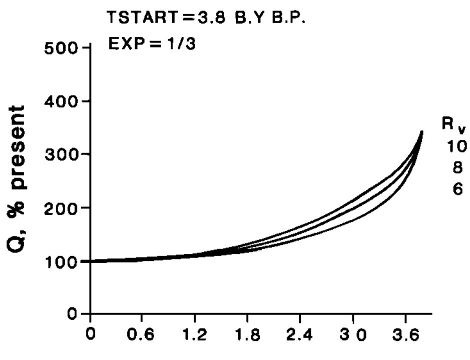

Fig. 7. Heat flow due to seafloor creation, Q expressed as a percentage of the present day value versus time before present. The initiation of continental accretion, TSTART equals 3.8 b.y. ago, EXP equals 1/3 and R_v equals 6:1, 8:1, and 10:1. Curves derived for EXP = 1/2 for the same values of R_v are visually indistinguishable and are therefore not shown.

creation to the total radioactive heat production for the last 3.8 billion years [Schubert et al.,1980]. At the present time, over 65% of the total terrestrial heat loss occurs as a result of plate creation at oceanic spreading centers [Sclater et al., 1981]. In conjunction with heat loss due to hydrothermal circulation, over 73% of all terrestrial heat loss occurs in ocean basins [Sclater et al., 1981]. Thus in terms of the inferred history of terrestrial heat loss, a linear rate of increase of the maximum age of oceanic crust at subduction, t_m, is quite reasonable.

DISCUSSION

Figures 2-6, derived from the model and demonstrating a fundamental relationship between the processes of sea floor creation and the origin of continents, allow us to make the following statements independent of the values chosen for R_v and erosion rate:

1. There was rapid continental accretion activity between roughly 3.8 and 3.5 b.y. ago.
2. There was a slower rate of accretion between roughly 3.5 and 2.0 b.y. ago.

3. The continental volume has been essentially constant since 2.0 b.y. ago.

If the ratio of the volume of igneous activity resulting from the subduction of old lithosphere versus that resulting from the subduction of young lithosphere, R_v, has been greater than 8, the model predicts a slowing of the rate of continental accretion between 3.5 and 3.2 b.y. ago. In fact, when R_v is set greater than or equal to 8, the model explains all of the following observed features of earth history:

1. Archaean terranes apparently record two major periods of rapid continental accretion, between 3.8 and 3.5 b.y. ago and between 3.1 and 2.6 b.y. ago [Windley, 1977; McCulloch and Wasserburg, 1978].
2. There are very few differences and many marked similarities between rocks from Archaean terranes and equivalent rocks from Phanerozoic terranes.
3. The total area of the continents has remained essentially constant for the past 600 m.y. [Wise, 1974] and probably for the last 2 b.y. [McLennan and Taylor, 1982; Allegre, et al., 1983], any variations having been within the range of 5-10%.
4. During the Archaean, there was apparently less silicic volcanism than at present and most Archaean volcanism consisted of a bimodal tholeiite-rhyolite type; there appears to have been a proportionately greater occurrence of plutonism relative to the present [Weaver and Tarney, 1982].

Our model predicts that continental surface area was somewhat greater approximately 1.4 b.y. ago (Figures 5 and 6), but it was not more than 10% greater, and the prediction is well within the limits of the geochemical methods used to estimate continental volume in the past.

According to our model, the apparent differences in volcanic and plutonic activity over time result from the differences in the nature and composition of resultant igneous activity due to the subduction of oceanic lithosphere of different ages. While differences in volume of igneous activity between areas of subduction of young and old lithosphere have been described [cf. Sacks, 1983; DeLong and Fox, 1977], documentation of compositional variations is sketchy, most of the evidence being inferential. Differences in composition have not been incorporated into our mathematical model, only differences in volume.

CONCLUSIONS

In this paper, we have presented a model in which the area-age distribution of ocean floor and the age at subduction of oceanic lithosphere have been related to the generation of continental material at subduction zones throughout the history of the earth. This model effectively explains features of Archaean tectonics and igneous activity in terms of plate tectonic processes. Major differences between the Archaean and the Phanerozoic were most probably caused by higher rates of mantle convection and radiogenic heat production resulting in faster spreading rates and/or greater total oceanic ridge length during the Archaean.

This model has the virtue of being readily testable. In particular, with the improvements in precision of present dating methods [Hanes 1983], it should be feasible to differentiate within greenstone belts between mafic and ultramafic rocks formed at oceanic spreading centers and those deposited in back arc basins as a result of subduction zone magmatism. A series of these measurements would provide empirical estimates for t_m at particular periods of earth history. It should also be possible to differentiate between the ages of emplacement of siliceous plutons and the eruption of calc-alkaline volcanics, making it possible to deduce the chronology of subduction and the changing nature (area-age distribution) of the subducting lithosphere over time.

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